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13. ABSTRACT *(Maximum 200 words)*

Applications of high-temperature superconducting (HTSC) materials, especially thin-film YBaCuO (123), to microelectronic devices have been limited by materials-related fabrication problems. Magnetic-flux-coupled devices are less limited by these problems but have not been widely explored. The innovation for this program was demonstration of a flux-coupled device that was: 1) simple to fabricate, 2) based on silicon substrates, 3) shows excellent flux-flow dynamics, and 4) can be implemented in switching or amplifying circuits. In Phase I we have demonstrated our potential for developing this device utilizing high critical-current YBCO thin films on yttria-stabilized zirconia (YSZ)-buffered Si substrates. Our devices are designed to take advantage of these new materials opportunities, are within realistic materials and fabrication constraints, and are projected to operate from dc to at least 10 GHz. The flux-flow devices (FFD) we have fabricated, include: externally-activated magnetic switch, superconducting transformer, and flux-flow (transistor-like) switch. The use of Si wafers not only allows high-quality films on large (or very thin) and inexpensive substrates, but also many design configurations with great potential for wafer-scale, hybrid integration with semiconductor electronics.

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"Superconducting Flux-Coupled Fast Switching Device From YBCO Films On Silicon"

FINAL REPORT

April 30, 1992

Contract No. F49620-91-C-0067

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"Superconducting Flux-Coupled Fast Switching Device From YBCO Films On Silicon"

-- SBIR PHASE I FINAL REPORT --

SDIO / Air Force Contract No. F49620-91-C-0067DEF

September 1, 1991 to February 29, 1992

TABLE OF CONTENTS

TECHNICAL SUMMARY OF PROGRAM

A new concept in the design application of superconducting magnetic-flux-coupled microelectronic thin-film devices was explored in this Phase I program. The basic idea for the Phases I, II, and III programs is to develop a structure for switching-circuit technology centered around active, three-terminal, high-temperature superconductor (HTSC), transistor-like electronic components. Fabrication of these devices centers on thin-film technology and features new, but highly successful, pulsed laser deposition (PLD) of HTSC films on silicon wafer substrates. The use of thin-films and Si substrates ensures upward compatibility with other microelectronic and discrete component technology, an extremely important feature for advanced electronic systems in R&D pre-commercial stages.

We have investigated the design, fabrication, and operating characteristics of a family of thin-film HTSC devices, which we will refer to as flux-flow devices (FFD). The central device-physics concept in FFD behavior is the resistive state induced in a type-II superconductor by the combined action (Lorentz force) of a magnetic field and electric current, which can cause flow of the quantized flux vortices in the superconductor film and thereby induce a voltage (Faraday's law). Reports of others have shown in detail that FFD analog (amplifier) operation with power gain is possible up to at least 10 GHz. Thus, the great promise which we identified in our Phase I proposal for fast flux-coupled switch microelectronics fabricated from thin-film HTSC.

In this Phase I program we have fabricated the first known HTSC FFD structures on silicon wafers, and we are among a very small number of groups known to have explored HTSC three-terminal FFD technology. Our devices and the characterizations we have done, have added important new evidence as to the details of the basic device physics, as is described in this *Report*.

This Phase I project has *successfully* demonstrated a coherent, promising and feasible plan for the R&D of a superconducting microelectronic device. Our results demonstrate FFD performance characteristics which compare quite favorably with competing technologies of semiconductor and low-temperature superconductor devices.

The technical effort was accomplished in six Tasks. First, we briefly review these as they were presented in the Phase I proposal. Then we describe in detail, task by task, the technical accomplishments we have made during the Phase I program. Finally, we conclude with descriptions of our research group, publications, and important assistance we have received from a consultant: Prof. J.I. Budnick.

SUMMARY OF TASK DESCRIPTIONS AND OBJECTIVES

The following is the *Work Plan* description, taken from the Phase I *proposal* of January 9, 1991.

TASK I - *Deposit films, pattern them, and evaluate single thin-links for magnetic field sensitivity.*

Objective - To obtain baseline information on the process issues for patterning of YBCO films into thin links.

Methodology - We will follow the established procedures for film deposition by PLD onto silicon, and patterning by wet etching.

Work To Be Performed - 1) Wet etching of films with photoresist into narrow lines. 2) Resistivity and critical current evaluation of the films and routine optical microscopy and SEM surface analysis to optimize the process parameters. 3) Additional patterning process evaluation for forming the weak-link regions. 4) Adapt the existing AFR cryostat and resistivity-measuring electronics for evaluation of the magnetic-field response (sensitivity) of individual thin-link patterned films. 5) Evaluate these for their magnetic field sensitivity.

TASK II - *Repeat the Task I process for simple directly-bonded pairs and evaluate the flux coupling.*

Objective - To obtain baseline information on the process issues for bonding of YBCO films on Si wafers into nearby pairs of thin links.

Methodology - Make preliminary tests of pairs of thin-link patterned lines pressed together with a thin epoxy dielectric between. Do current-voltage (I-V) curve testing for the pair of films to evaluate their flux coupling. Make preliminary evaluations of the switching-speed performance of this four-terminal device.

Work To Be Performed - Pairs of films patterned under Task I will be pressed together with a thin layer of bonding agent, and tested for flux coupling from 300 to 4.2 K in the four-wire resistivity cryostat. Construct a cryostat probe with a pair of coaxial lines to allow pulse propagation in and out with rise times at least as short as 10 ns.

TASK III - *Establish passivating (cap) layers for the thin-link YBCO film surfaces by adapting the results of other current SBIR work at AFR.*

Objective - Preliminary tests will be made of SiO_2 and ZrO_2 cap layers deposited on YBCO thin link films.

Methodology - Full coverage films are deposited in the usual way, patterned as described above, and returned to the PLD system. The passivation layers will be deposited at much lower temperatures than used for the initial depositions, i.e., kept below 300 °C. Again, the results of the other SBIR contract at AFR, currently studying such issues, will by used extensively here.

Work To Be Performed - 1) Deposit SiO_2, ZrO_2, or other dielectric films at low T on top of the patterned YBCO films. This can be done with the PLD system. 2) Evaluate their impact on T_c and J_c of the YBCO, test their dielectric strength and absence of pin holes. 3) Finally, check their suitability as protective passivation layers under the condition of heating to 300 °C (for polyimide curing), and cooling repeatedly to 77 K.

TASK IV - *Test the suitability of polyimide for bonding the YBCO thin-link films, again by adapting the results of other current SBIR work at AFR.*

Objective - Preliminary tests will be made of polyimide films spun on and cured over the passivated YBCO films. We will demonstrate the extent of their general suitability for bonding agents between patterned films.

Methodology - We will begin with the standard polyimide process of room temperature spin coating in a solvent, followed by drying. The curing will be performed first at the manufacturer's specified temperature (typically 250-300 °C). If, after evaluation of these coatings and their effect on the YBCO film T_c and J_c, some degradation is noted, lower curing temperatures will also be tried. Again, the results of the other SBIR contract at AFR, currently studying such issues, will by used extensively here.

Work To Be Performed - 1) Spin on and cure polyimide or similar material over the passivated YBCO films, and test the super-film T_c and J_c. 2) Test the fracture resistance of the film multilayers with cycling to at least 77 K.

TASK V - *Design several novel structures of this device within the constraints and new opportunities occurring as a result of the Task I-III work.*

Objective - To generate several possible design expressions of the flux-coupled fast switch, and evaluate them against the potential for a high ratio of performance to fabrication effort.

Methodology - This task will use the results from Tasks I-IV as a guide to project the practical limits of feasibility for possible device architectures. Against this we will project classic flux-coupled device designs as well as several novel ones.

Work To Be Performed - A summary table and document will be drawn up for the relevant materials fabrication knowledge available in the literature, from other past and current related R&D work at AFR, and especially from the Tasks above. A team of AFR personnel experienced in materials and superconducting devices will be assembled to brainstorm new designs. In subsequent meetings we will evaluate these and form a priority list.

TASK VI - *Fabricate one of these devices and evaluate its performance against the design expectations.*

Objective - To fabricate a full featured device and evaluate its performance against the design expectations, so as to tighten the design/fabrication/performance loop for this type of device.

Methodology - We will follow the best methods available as identified in Task V and use the fabrication processes explored in Tasks I-IV.

Work To Be Performed - This Task will start with substrate preparation, go to buffer and superconductor film, patterning, passivation coating, wafer pair bonding, and lead attachment. Device evaluation will measure the superconducting and flux coupling properties, including the switching speed, of the device. Finally, we will draw up a summary evaluation document of the actual performance in comparison to the design expectations.

PROGRESS REPORTS BY TASK

TASK I - *Deposit, pattern, and evaluate thin-film single links for magnetic field sensitivity.*

Facilities and Films

Working primarily with support of existing SBIR contracts from DOE [1] and DARPA [2], we have, in the time since writing the proposal for this contract, fully completed the design, construction and testing of our new facility for pulsed laser deposition (PLD) of thin films. Our high-temperature superconductor films of $YBa_2Cu_3O_{(7-\delta)}$ (YBCO) are now of very good quality, when deposited on "easy" substrates such as $SrTiO_3$ (STO), $LaAlO_3$ (LAO), MgO and yttria-stabilized zirconia (YSZ). On STO and LAO our films have superconducting transitions with zero-resistance (T_{co}) as high as 90.7 K, normal-state slope ~3.0 between 300 and 100 K. On MgO substrates, our YBCO films, ~ 100 nm thick, have critical-current densities J_c ~ 5×10^5 A/cm^2 in zero field at 77 K measured both by SQUID magnetometry on unpatterned films and by transport current on narrow lines etched into the film.

Work on the much more difficult Si-wafer substrates has also been very successful. Since initiating our PLD system in February of 1991, we have deposited over 200 films of YBCO on YSZ-buffered Si using the Xerox PARC methods [3,4]. Our YSZ buffer films have shown high quality x-ray diffraction (XRD), with only the (001) orientation present and omega rocking curve widths below 0.6° (the XRD was done at Stanford by D.K. Fork). This is equal to the current world's record for this film and substrate system [3]. Over the second half of this contract period, we have improved the quality of our films on Si wafers. To some extent this was made possible by adjusting the PLD recipe so that the YSZ and YBCO films could be formed much thinner than we had done at first. YBCO films, ~ 50 - 70 nm thick, deposited on (50 nm) YSZ-buffered Si substrates have reached the following quality factors: T_{co} ~ 89.0 K, transition width ~ 1.1 K (10-90 %), normal-state slope ~2.7 [R(300K)/R(100K)], and transport J_c ~ 2×10^5 A/cm^2, for patterned lines in self field at 77 K. By research laboratory standards, films of this quality are now made "routinely" at AFR.

Typically, our films are deposited onto silicon wafers that are 1-cm square and 15-16 mil (~ 400 µm) thick. Using wafers pre-thinned by Virginia Semiconductor, we have found methods of mounting and handling so that our standard PLD process can be used with wafers 75, 25, and 2 - 4 µm thick. For all of these four Si thicknesses, we have been able to obtain high-quality superconductivity in the YBCO films. Presently, the very thin wafers are difficult to handle and process, but they have provided an important proof-of-principle as to the nature of PLD films deposited onto them. An R(T) curve measured for a YBCO film on nominally 3-µm thick Si, is shown in Figure 1, below [5,6].

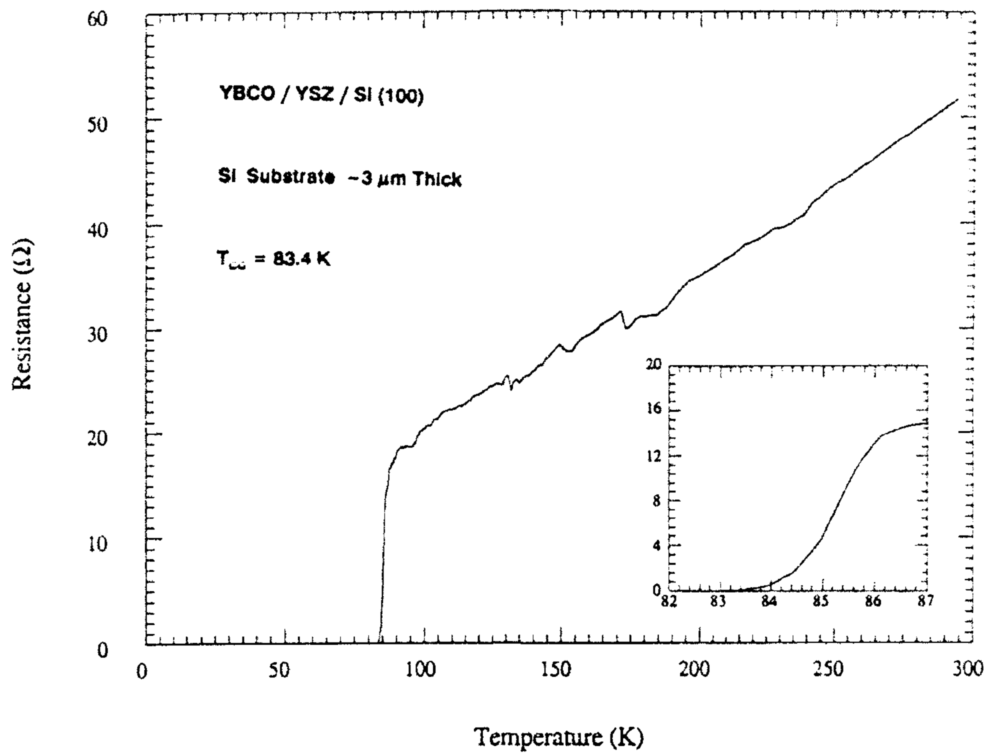

Figure 1. Resistance measured by four-point probe method on a YBCO film deposited on a YSZ-buffered Si(100) wafer substrate. The Si wafer was ~3 μm thick. The inset show the transition region on an expanded T scale. This film was unpatterned, as tested here.

We also now have a fully functional YBCO film patterning facility. At AFR, masks are drawn by CAD, printed on a laser printer, photographed at ~ 20:1 reduction onto Kodak *Technical Pan*, and the resulting 35-mm film negatives used as contact masks. In our "yellow room" these contact masks are printed onto positive photoresist (Shipley 1400-series), the resist is developed, and the YBCO etched with EDTA solution (an organic acid) in an attenuated ultrasonic bath. The lithographic process design limit is for ~ 2 μm, and is presently limited to ~ 10 μm by the roughness of the etched YBCO edges. To date, our narrowest YBCO lines and gaps, etched and functioning successfully, have been ~ 30 μm wide. Gold films on Si have been etched into lines of ~ 2-μm edge resolution, as observed by scanning electron microscopy (SEM). We are in the process of upgrading our yellow room to include a class-100 clean bench, which will house all of the lithography apparatus. Laser-ablation patterning or trimming will be possible soon, using our pulsed YAG.

Wet-etch patterning has also been successful for films on all of the thinner Si wafers. Simple IR detection by bolometric response was demonstrated with one of the patterned YBCO films on 3-μm thick Si pieces. We made this latter test since we have experience with these devices [1], they are simple to make, and provide an additional test of material quality. YBCO films on ultrathin Si provides a number of interesting technological possibilities, including the fast flux-switch devices. To our knowledge, we are the first to deposit and report high-quality YBCO films on 3-μm thick Si. This work was reported at the Fall 1991 MRS meeting [5].

Early in February 1992 we began a collaboration with Prof. H.D. Drew's group at the *Center for Superconductivity Research* at the *University of Maryland.* They have extensive expertise and facilities for the study of HTSC films in the far infrared (IR). They studied one of our YBCO films on YSZ-buffered Si over the wavelength range of 50 - 330 μm, i.e, extending down to the THz regime. As is detailed in a manuscript we submitted jointly to *Physical Review Letters* and in a talk given at the March 1992 *Amer. Phys. Soc.* meeting [7], the substrate and buffer film are very transparent to IR in this wavelength allowing detailed measurements on thin (~ 60 nm) YBCO films. The Si wafers are commercial (CZ processed) with 1 - 10 Ω-cm resistivity at 300 K, but as we have found, by 77 K all the carriers are essentially frozen out and the wafers have very low loss rf characteristics at millimeter and shorter wavelengths. The wavelength-dependent transmission was fit very well by a Lorentzian based on the London model of superconductivity in the far IR (well below the gap) and Drude free-electron optical conductivity. The free parameter in that fit is related to the thickness of the film and the London penetration depth λ_L, which had a low-temperature limiting value of 170 - 200 nm and a T dependence in excellent agreement with the BCS expectation: superconducting fraction $f = 1 - (T/T_c)^4$. These results help to establish: 1) the properties of our YBCO film and substrate system at THz frequencies, and 2) the depth into which magnetic fields will penetrate our YBCO films on Si.

We have most recently collaborated with Prof. H. Zhang's group in the Department of Materials Science at *Northwestern University*. Their considerable skills and experience were very helpful in transmission electron microscopy of some of our thin-film samples using their new state-of-the-art microscope. These results, while preliminary as of this writing, show very high-quality lattices at atomic resolution, for the YSZ and YBCO films, and give precise film thickness data.

Flux Devices

The primary superconducting devices fabricated and tested for this program are listed in Table I. Most of the films were made on Si substrates, but one was made on a $LaAlO_3$ wafer, since the film microstructure is known to be quite distinct on each different type of substrate. In the Table, the three devices FFD # 1, 3 and 5 were simple 4-point contacted films, patterned with a "T" shape, as seen in Figure 2. Device # 4 was a very similar pattern, but without the "T", i.e., an "I" shape. The last three (FFD # 6 - 8) were fabricated with the "T" and an electrically independent "control line" of superconducting film nearby on the plane, as discussed in detail below under Tasks V and VI.

TABLE I. Flux-flow devices (FFD) fabricated and tested for this project. The film widths *w* are estimated from the photolithography masks, and the film thicknesses *t* are estimated from the PLD rates for ablation and deposition. A "-" suffix to the *t* value indicates that the film was intentionally thinned with a second lithographic mask and etch step.

FFD #	Sub-strate	*w* (µm)	*t* (nm)	Contacts & Pattern	T_{co} (K)	I_c(77K) (mA)	FFD Tests Performed
1	YSZ/Si	200	160	4-point "T"	85	6	I-V(77), $\delta V(B_{ex})$
3	LaAlO	200	80-	4-point "T"	90.5	72	$\delta V(B_{ex})$
4	YSZ/Si	70	160	4-point "I"	78	0.005	I-V(7&77), $\delta V(B_{ex})$
5	YSZ/Si	200	60	4-point "T"	85	0.02	I-V(77), $\delta V(B_{ex})$
6	YSZ/Si	200	60	6-point "c-T"	87.5	2.3	I-V(7&77), $\delta V(B_{ex})$, δV(c-I)
7	YSZ/Si	200	30	6-point "c-T"	~77	0	I-V(77)
8	YSZ/Si	200	40	6-point "c-T"	83.6	13	I-V(T), δV(c-I)

We call all of these devices by the generic name: "Flux-Flow Devices", but all are based on the flow of magnetic flux, in the form of vortex cores or tubes that penetrate through thin type-II superconductors when they are in the mixed state. There is considerable controversy about the detailed description and models of the HTSC materials in the mixed state (between H_{c1} and H_{c2}) [8], but here we need only observe that in the mixed state the material will not show a voltage drop when under bias, until that current exceeds some minimum value, referred to as the critical current I_c. In this work we have chosen the commonly defined conditions for identifying this voltage-drop onset, i.e., the 1- μV criterion. Above I_c, the material shows a flux-flow resistance [9], where the Lorentz force on the vortices exceeds the pinning force and the subsequent viscous flow causes dissipation effects that appear as a voltage drop. These measured values of I_c at 77 K are reported in Table I along with a summary list of the characterization test performed on each device. The voltage drop for films under very small bias [R(T)] was measured for all devices, and current-voltage curves at 77 K [I-V(77)] were measured for most devices. The resistance R from 300 to 77 K for FFD # 3 and 6 are shown in Figures 3 (a) and (b).

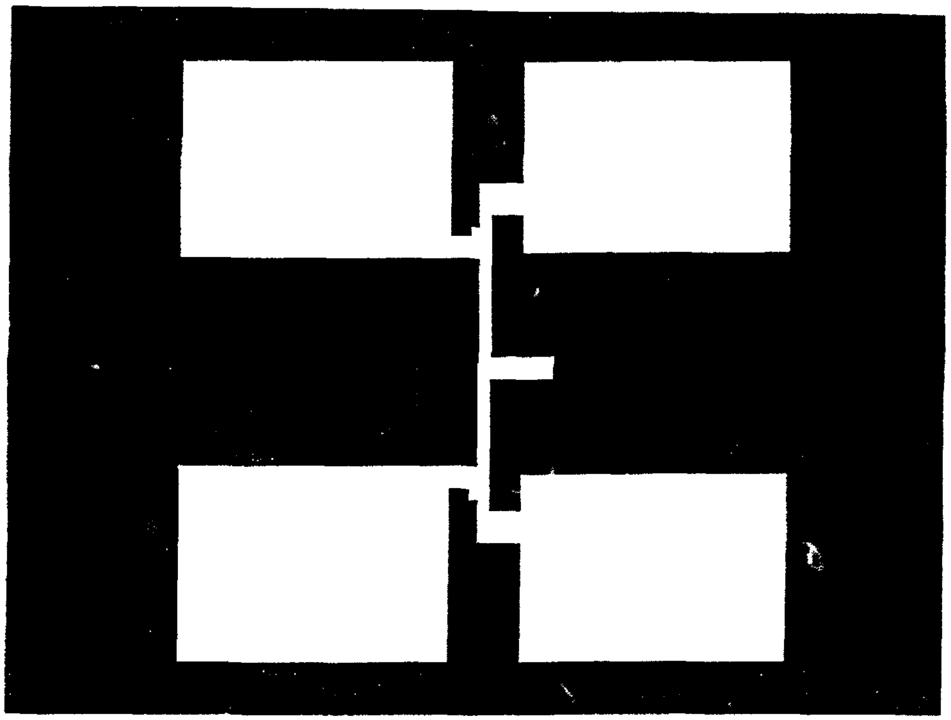

Figure 2. Photolithography mask used for the "T" shaped flux-flow devices (FFD) # 1, 3 - 5. Two of the large four squares are pads for connection of the external current source, and the other two are for voltage-sensing. The central region is the FFD itself, where the "T" shaped structure is seen. The smallest line width, as printed onto the device, is ~ 200 μm.

At low temperatures our film devices show the expected current-voltage curve shape, as can be seen in Figure 4. At both 7 and 77 K the curvature of the I-V data, as it rises from I_c, is consistent with the absence of Josephson effects, especially SIS and SNS junctions or weak links. All of our film samples, to date, have this same curvature of the I-V data. There the curve for FFD # 6 at 7 K has a slope (the differential resistance) that indicates a declining differential resistance ($R = \delta V/\delta I$) as I increases well above I_c. The limiting functional shape at high currents is a power law with an exponent ~ 5.0 at both 7 and 77 K. At 7 K and $I_S/I_c = 1.3$, the sample at reaches R = 0.22 Ω, while at 77 K and $I_S/I_c = 1.3$ the sample reaches R = 0.13 Ω. At the highest current ($I_S/I_c = 2.0$) reported for 77 K, the R = 0.73 Ω. The data actually recorded in the figure do not go to higher I values, since thermal runaway was observed there.

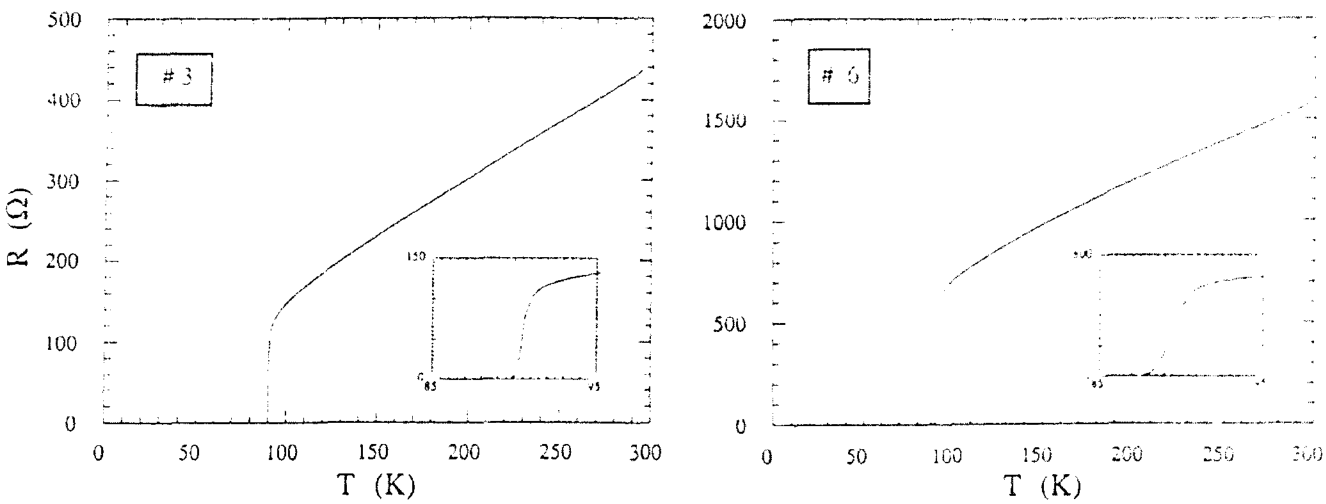

Figure 3. Resistance measured by four-point probe method on YBCO films deposited on: a) $LaAlO_3$ wafer and b) YSZ-buffered Si wafer substrates. The insets show the transition regions on an expanded T scale. The films were patterned.

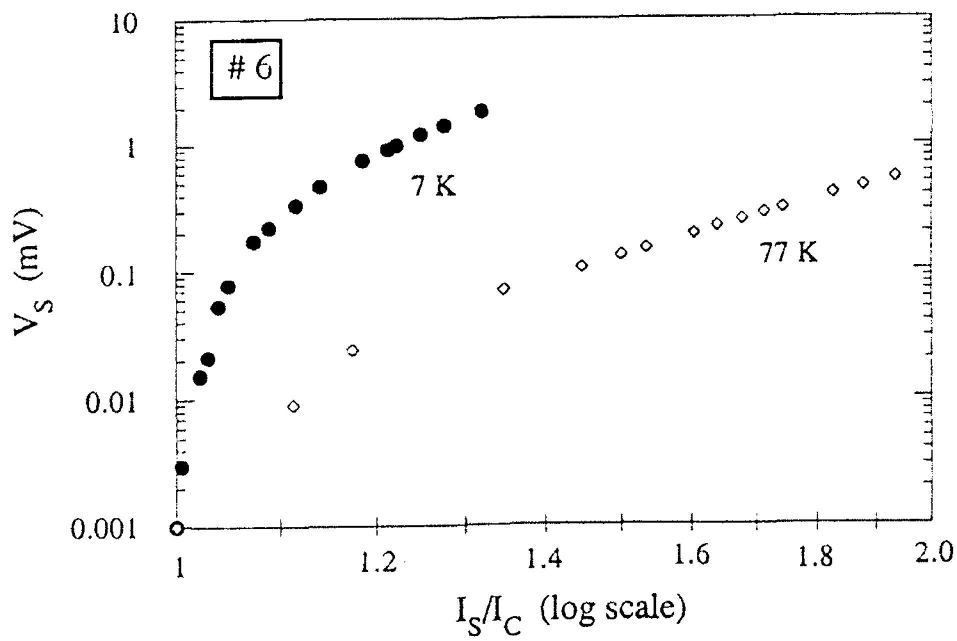

Figure 4. Current-voltage I-V curves for FFD # 6 at 7 K (filled symbols) and 77 K (open symbols). Both axes are **log scales** and the currents are normalized by the critical values I_c, 40 and 2.3 mA, respectively.

Partly due to the very small values of H_{c1} in HTSC materials, even modest magnetic fields (B) can cause a measurable flux-flow resistance (R). This will appear as a change in the voltage drop for a superconducting film biased into the mixed (resistive) state. Table I indicates which devices were tested for this effect, i.e., the $\delta V(B_{ex})$ test. We have explored this effect for the purpose of demonstrating a simple switch, but also to establish a base line for the true magnetic field sensitivity of our superconductor lines. The detailed results of these tests are listed in Table II, and are discussed below.

Under very small bias currents, the voltage drop on these films is zero below a temperature T_{co}. In Figure 5 is shown the effect of applying a small magnetic field (7.8 mT) perpendicular to the sample by use of the external solenoid coil. There is little change in T_{co} and only a small change in the transition region (above T_{co}). This is characteristic of all our devices.

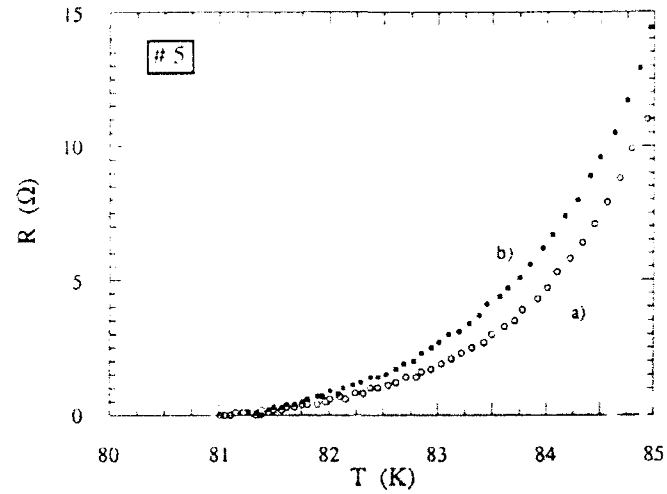

Figure 5. Resistance measured by four-point probe method on FFD # 5 in the region near T_{co}. Separate curves are shown for zero external magnetic field (circles) and for a current of 1.0 A (squares) in the external solenoid coil. The estimated field is 7.8 mT (78 G).

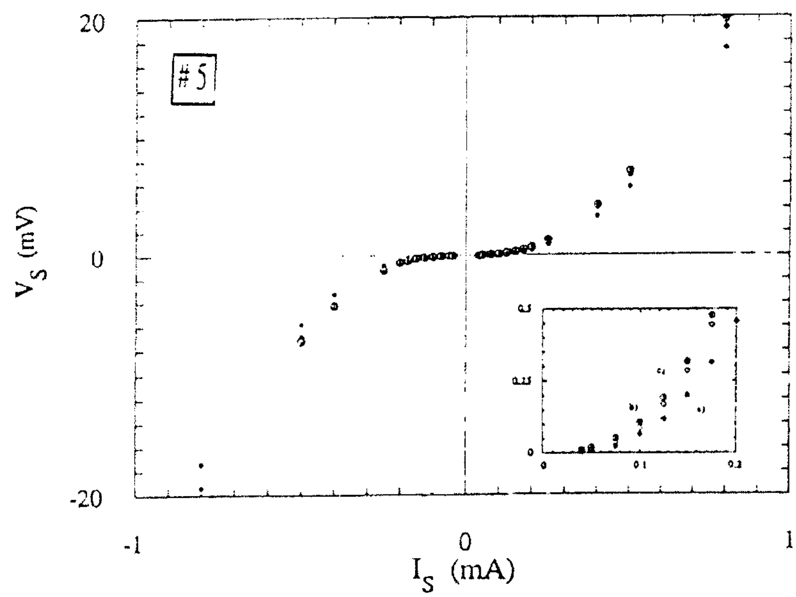

Figure 6. Current-voltage I-V(77) curve for FFD # 5 at 77 K. Separate curves are shown for zero external magnetic field (solid diamonds), and currents of 1.0 (open diamonds) and 1.4 A (circles) flowing in the external solenoid coil. The estimated fields are 7.8 and 11 mT.

The current-voltage curves in the superconducting state of these film devices, are altered by the external field when the bias is above the empirical I_c value. Figure 6 shows the I-V(77) curve for FFD # 5, at 77 K, i.e., well below T_{co} for this device. The results are symmetric in bias current and in field direction.

The flux-flow voltage induced by the external field in our devices was found to be essentially a linear function of the coil current and hence the field strength. This is illustrated in Figure 7 for FFD # 3 under several bias currents.

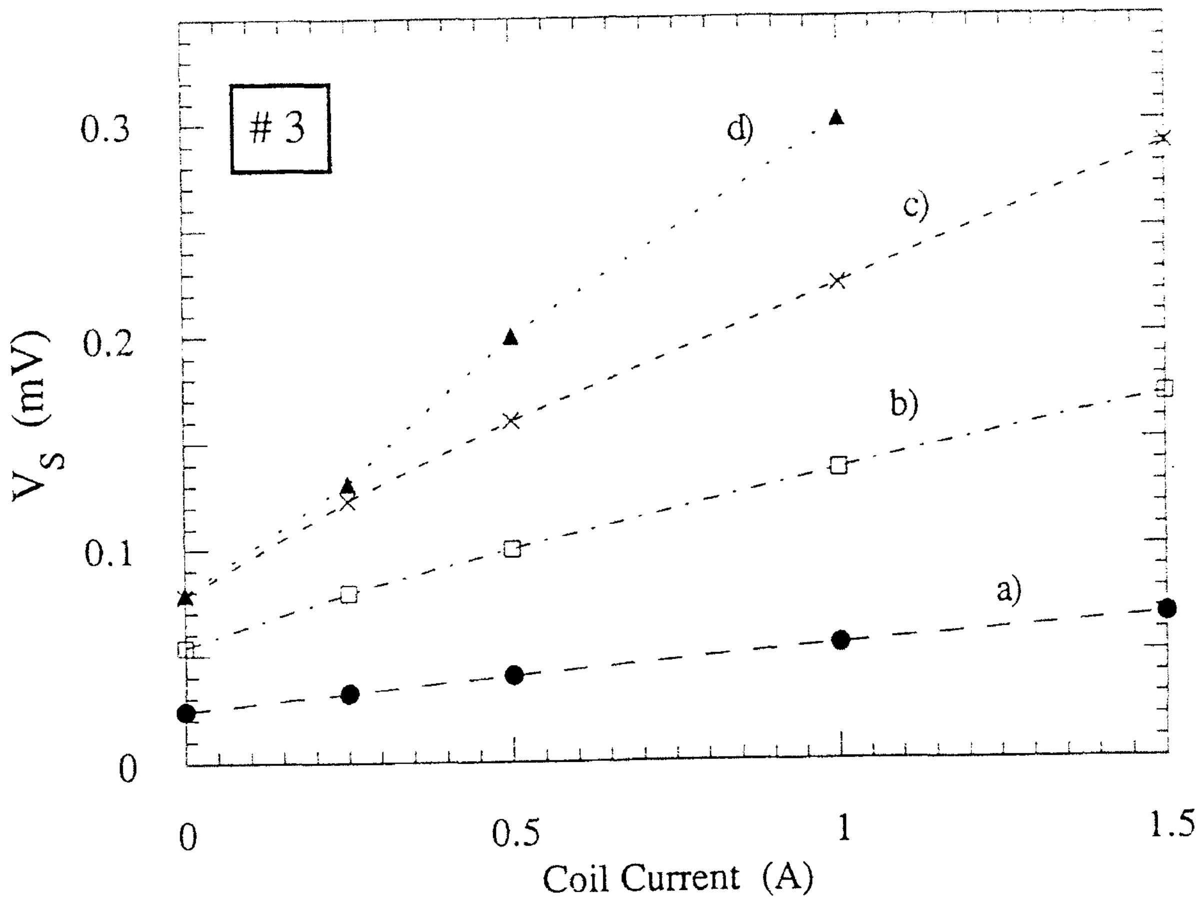

Figure 7. Flux-flow voltage for FFD # 3 at 90 K, i.e., just below T_{co}. The voltage is seen to increase with the current flowing in the external solenoid coil. Separate curves are shown for bias currents of a) 0.5, b) 0.75, c) 1.0 and d) 1.3 mA. The estimated magnetic field is 7.8 mT at 1.0 A.

The external-field flux-flow voltage measurements were used to estimate the differential magnetoresistance and related parameters for FFD # 1 and 3 - 6. Table II summarizes the numerical results for these (4-point-contact) tests of the FFD. In some cases, large (over 100%) fractional changes in the voltage drop ($\delta V/V_0$) can be induced by the small B field. In other cases voltage-to-field sensitivity ($\delta V/\delta B$) can be made quite large (in the range of volts per tesla). The former is a switch-like or digital function and the latter an amplifier or analog function for the FFD. Finally, the differential magnetoresistance reaches values of 0.5 Ω/mT or 0.05 Ω/G (per gauss).

TABLE II. Differential magnetoresistance of the flux-flow devices (FFD). These results were measured using an external solenoid coil and dc current. The calculated field was 7.8 mT (i.e., δB = 7.8 mT = 78 G) and acts perpendicular to the plane of the sample. $\Delta T = T_{co} - T$. δV is the increment in V, above V_o, when the external field is activated. $\delta R = \delta V/I_o$ is the differential flux-flow resistance.

FFD #	T (K)	ΔT (K)	I_c (mA)	I_o (mA)	V_o (mV)	δV (mV)	$\delta V/V_o$ (at I_o & δB)	$\delta V/\delta B$ (at I_o) ($\mu V/mT$)	$\delta R/\delta B$ ($m\Omega/mT$)
1	77	8.0	6.0	9.8	5.2	0.38	0.73	50	150
3	89.1	1.4	1.1	4.0	0.08	0.012	0.15	1.5	5
	89.4	1.1	0.65	4.0	0.127	0.13	1.0	16	60
	89.7	0.8	0.35	4.0	0.976	1.1	1.1	140	314
4	77	1.0	0.005	0.09	0.95	0.35	0.37	45	500
				0.6	82	3.6	0.044	460	770
5	77	8.0	0.02	0.8	16.5	1.8	0.11	2200	350
6	77	10.5	2.3	6.4	2.5	0.9	0.36	120	360

TASK II - *Repeat the Task I process for simple directly-bonded pairs and evaluate the flux coupling.*

We have fabricated a flip-chip dc transformer from two samples of YBCO films deposited, patterned and tested separately. One, used as a 4-point probed secondary (sensor) line, was deposited on an $LaAlO_3$ (LAO) wafer. The second was a YBCO/YSZ/Si film structure, and it was used as the transformer primary (control). Patterning was similar to the shape of Figure 2, above.

The device was tested at 77 K, by direct immersion in liquid nitrogen, so as to avoid any possibility of temperature differences developing across the poor thermal contact of the adhesive. Due to fabrication difficulties, data on the device performance is limited. However, the secondary line did show I-V curves similar to those reported on the FFD above. Current in the primary caused an increase in the voltage in the secondary when the secondary was biased well above its critical value. The output voltage was nearly a linear function of primary current.

TASK III - *Establish passivating (cap) layers for the thin-link YBCO film surfaces.*

Work we have done partially under the DOE and DARPA contracts [1,2], and completed during the first third of the present contract, developed methods to passivate our YBCO films using YSZ or MgO overcoat layers. These passivation layers are deposited by PLD onto shadow-masked YBCO/YSZ/Si after YBCO-film patterning and Ag-pad contacting. The final deposition of YSZ is done with the sample held at ~ 100 °C in vacuum or low oxygen pressure. We have demonstrated that these overcoat films render the narrow lines of YBCO films water proof and free of pinholes that could cause shorts to the YBCO from metal films deposited onto the top surface. In addition, the success of passivation with YSZ was demonstrated in the processing and far-IR analysis of the samples sent to Univ. Maryland (see description under Task I, above). That film sample handsomely survived mounting (film face down) and lapping of the backside of the substrate silicon wafer (to form a wedge shaped wafer) [7].

TASK IV - *Test the suitability of polymers (polyimide) for bonding the YBCO thin-link films.*

Continuing with the DOE and DARPA contracts [1,2], we demonstrated that the passivated film structure (YSZ/YBCO/YSZ/Si) can have a second Si wafer (with films of its own, if so desired) bonded on top of the overcoat layer (YSZ) without degradation of the superconductor properties. We have tested several adhesives, including: photoresist, GE #7031 varnish, and rubber cement. All of these are compatible with the passivated YBCO films and none crack or fracture upon thermal cycling from 300 to 77 K and back, repeatedly [2]. Since a variety of other adhesives were successful, we have not tested polyimide itself, but its unlikely to be substantially different in these respects. A very useful polymer for temporary bonding is photoresist, since it can be spun on to the surface, resulting in a uniform film of known thickness.

We have used polymer adhesive to bond together two pieces of Si wafer each one of which had a YSZ and YBCO film pair deposited onto it. Prior to bonding the films were patterned into narrow lines with 4-point probe contacts and YSZ passivation films deposited over the central active region of each film. Upon bonding this pair, the R(T), I_c, and J_c did not change from the values measured before bonding.

TASK V - *Design several novel structures of this device within the constraints and new opportunities occurring as a result of the Task I-III work.*

After preliminary evaluation of the data for Tasks I - IV, above, and a search of the literature, we elected to concentrate our efforts on FFD designs based on the vortex flux-flow transistor (VFFT) which John Martens and others (collaboration of Sandia National Lab., Univ. Wisconsin, Hypres Inc., and A.T. & T.) have reported [10-13]. Indeed, it was work by this same group about two years before that had inspired the core of the Phase I proposal that was the basis for this present contract [14].

In that work, as it has evolved over the 2 or 3 year period, they have demonstrated their VFFT in Nb-based and in YBCO and TlCaBaCuO ceramic superconductor materials. They propose a mechanism of magnetic control over flux flow that allows the current in a "control line" to influence the I-V curve of a nearby superconductor line [10]. These devices have been shown by them to exhibit power gain of over 20 dB at frequencies in the 7 - 10 GHz microwave region [11]. As they have pointed out, these VFFT devices, which they are investigating, are one of a family of superconducting flux-flow transistor-like devices [12].

In HTSC thin-film technology we felt that there was considerable advantage to any single-layer superconductor-film device that showed promising three-terminal device (i.e., transistor-like) characteristics, as do those from the Martens' group [10-14]. Hence, we have made our initial FFD patterns similar to theirs. These have been tested and the results are reported under Task VI, below. In addition, we have designed several variations of the single-layer superconducting film FFD configurations in the three-terminal family. Some form the basis for the next stages of the larger research program, i.e., the Phase II, and will be explored there.

All of these FFD (mask) patterns are shown in Figure 8, and that in 8 (a) was used to pattern the FFD # 6 - 8, discussed below. In Figure 8 (a) and (b), the control line (gate) is electrically isolated from the sensor line. In both, the sensor is in a "T" shape, but in 8 (b) we propose inducing a weak-link type of structure down the length of the "T". In the design of Figure 8 (c), the control line is terminated to the body of the sensor line so that the sensor-line bias and the control-line currents share a common termination. Although the two currents must now flow in parallel, flux vortices can flow directly from the control line into the sensor line. In the last panel (d) of Figure 8, the control current not only flows via one of the sensor bias terminals but also flows down the length of one side of the sensor "T" line. If the detailed geometry of the magnetic field, induced by the control-line current, is a critical feature in device behavior, this pattern should help to reveal that point. In Figure 8 (d) we have also included a simple 4-point contacted line, patterned to narrower dimensions but without weak links, that can be used to monitor film quality, etc., as the device is used over time and in various ways. Many more pattern variations and device-design opportunities are available, and hence potential for considerable engineering improvement and manipulation.

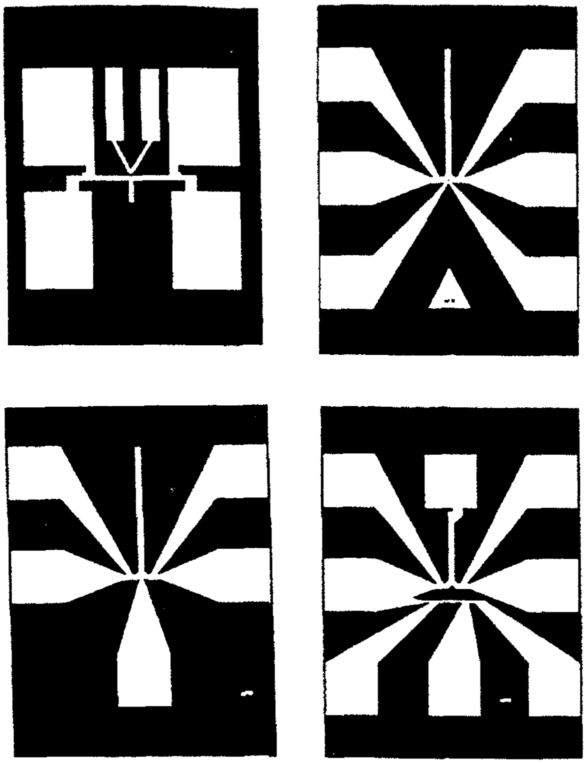

Figure 8. Photolithography masks for various FFD designs. Taken clockwise, in (a) is the pattern used for the "c-T" shaped flux-flow devices (FFD) # 6 - 8. In (b) - (d) are other possible FFD designs, as discussed in the text. The length of the edge between outer corners of the contact pads is nominally 9 - 10 mm, while the narrowest lines are 100 - 200 µm, as shown.

TASK VI - *Fabricate one of these devices and evaluate its performance against the design expectations.*

We have purchased a new cryostat from Janis Research to augment our present system for film measurements. Our first cryostat was fully custom built and covers the range of 4.2 to 300 K, but only allows relatively small samples and a limited number of sample-to-lab. wires. The new cryostat, which is cooled with liquid nitrogen, was purchased by AFR and put into service during this contract. It is equipped with a custom built sample mounting finger, and now allows testing and evaluation of high lead-count devices and the potential for up to at least 50-mm diameter wafers. It was used to evaluate the three-terminal FFD designs (# 6 - 8) that have the "c-T" shape shown in Figure 8 (a), and noted in Table I.

We have fabricated *three* of the FFD in the "c-T" shape of Figure 8 (a), and they are FFD # 6, 7, and 8. For both # 6 and 8, we ensured that the control line was electrically isolated (by several MΩ) from the sensor line. The # 7 was not fully isolated and only approached T_{co} by ~ 77 K. It was useful only to verify that for three-terminal FFD with non-isolated gates, the normal state (any $T > T_{co}$) is characterized as a simple ohmic resistor network.

The FFD # 6 was tested in both the external magnetic-field (solenoid coil) 4-point configuration and in the control-line activated, 6-point (3-terminal) configuration. The last entry row in Table II, above, shows the results of the external field tests. In Figure 9 are showr, the I-V curves for FFD # 6 measured in both cryostats, at similar T, and with external field or gate current applied. Note that these sets of data (in the two cryostats) were at nominally 80 and 81 K, which shifts the I-V curves and the empirical I_c values. Nonetheless, valuable comparisons can be made. At higher values of the sensor bias current, I_S ~ 4 mA, the I-V curves for this FFD **both** shift upward by ~1 mV upon application of 1 A to the solenoid (i.e., 7.8 mT field) **or** 21 mA to the gate line. SEM analysis of FFD # 6 showed that the isolation gap between the sensor and gate lines was ~ 60 µm wide. The estimated magnetic field 60 µm away from a flat conductor carrying 20 mA is only ~ 0.07 mT (0.7 G). Thus, it appears that **our *gate* FFD is about two orders of magnitude more sensitive** than the external field FFD configuration. As seen in Figure 9, this enhanced sensitivity is even greater for lower bias currents in the sensor line.

A very similar result was observed for the effect of gate current on the I-V curves of FFD # 8, as shown in Figure 10. There are shown I-V curves at three temperatures: 79, 81, and 82 K, each without gate current, and at 81 K with 7.9 mA in the gate line. Clearly, the presence of a gate current I_G just shifts the I-V curves by a constant multiplicative factor, at $I_S > I_c$.

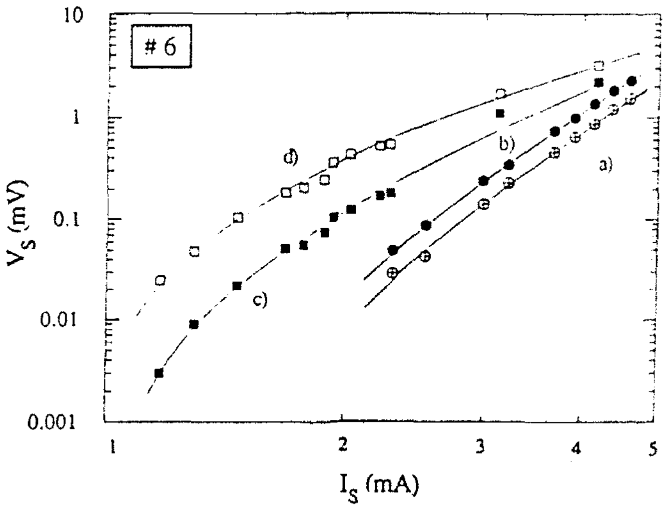

Figure 9. Current-voltage (I-V) curves on log-log scales for FFD # 6 at: (a & b) 80 K in the old cryostat and (c & d) 81 K in the new (Janis) cryostat. Separate curves are also shown for (a) zero external (solenoid coil) magnetic field, and (b) 7.8 mT, as well as (c) zero, and (d) 21 mA current in the gate line.

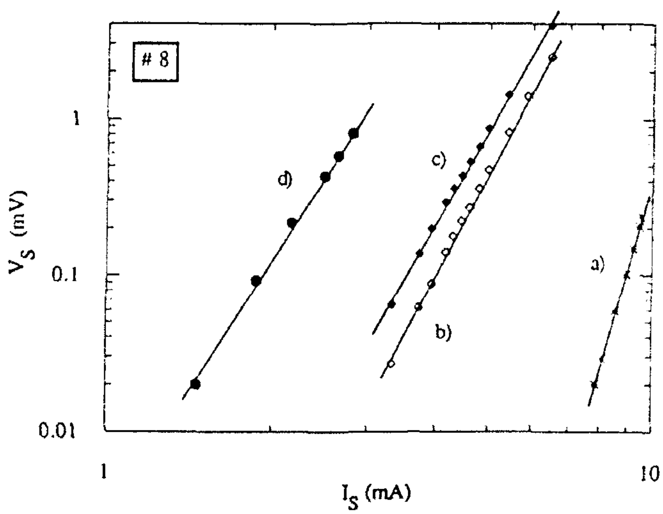

Figure 10. Current-voltage (I-V) curves for FFD # 8 at: (a) 79.0 K, (b & c) 81.0 K, and (d) 82.1 K. Separate curves are shown for the 81.0-K data, with: (b) zero current, and (c) 7.9 mA in the gate.

More detailed characterization of the transfer function (gate current into sensor voltage) is shown in Figures 11 (a) - (c) for FFD # 8. The sensor voltage (device output) is seen to increase as a power law with the gate current. The power-law exponent is ~ 2.0 for this FFD (# 8), except near T_{co} and I_S just above I_c, where the exponent increases, **greatly enhancing the FFD sensitivity**. We also found exponent ~ 2.0 for FFD # 6 under conditions not too close to T_{co} and I_c. The largest slope observed was ~ 7.0 for FFD # 8 at 82.1 K, I_S = 1.37 mA, and I_G = 8 - 10 mA, as can be seen in Figure 11 (c). This is to be compared with the linear (exponent one) behavior we have observed for FFD switched by the external magnetic field, as in Figure 7, and the linear behavior demonstrated by the collaboration at Sandia [10-14]. In the latter case, the devices were thinned, over the length of the "T" structure, such that the I-V curves and transfer functions were nearly linear [10,12].

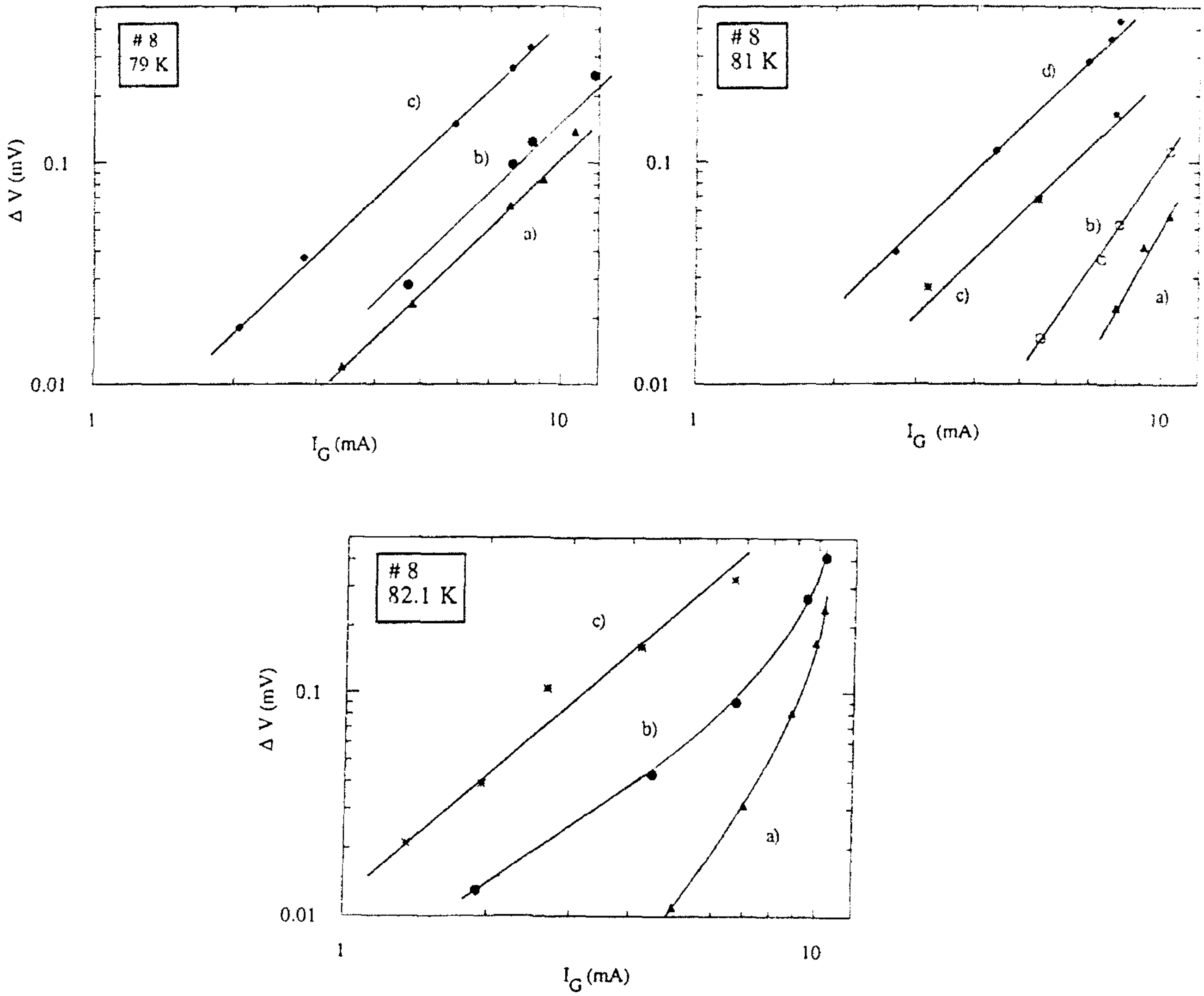

Figure 11. Current-voltage (I-V) transfer-function curves for FFD # 8 at: (A) 79.0 K, (B) 81.0 K, and (C) 82.1 K. The sensor voltage change ΔV is plotted for various currents in the gate line I_G, while the FFD sensor is biased (I_S) by the following currents: (a) 9.94, (b) 8.88, and (c) 8.53 mA in panel (A); (a) 3.0, (b) 3.5, (c) 4.25, (d) 5.0 mA in panel (B); and (a) 1.37, (b) 1.6, (c) 2.28 mA in panel (C).

We hypothesize that the enhanced sensitivity we have observed, and the parabolic (or greater) dependence of the sensor output voltage upon the gate current, occurs because of the well-known surface barrier to flux entry in type-II superconductors together with geometric factors in the HTSC film de-magnetization. In our experiments, the external field enters on the broad area of the sensor film surface, while the field from the gate line enters the edge of the sensor. Wet etching causes considerable roughness at the micron scale in YBCO film edges and this will substantially reduce the surface barrier to flux entry. This enhancement effect seems ripe for exploitation to improve FFD performance.

As discussed above, we have ruled out direct-heating thermal effects, since at high enough bias, well above the data actually recorded in these figures, an onset to thermal runaway was observed. In those situations the voltage began to drift upward, apparently without limit, on a few-seconds time scale. Additional evidence as to the thermal properties of our YBCO films on Si wafers comes from the extensive measurements we have made for the IR detector (bolometer) programs [1,5,6]. The typical thermal time constant for our films on Si is measured directly with those devices.

Another significant observation, based on Figures 11, is that although the sensor line must be biased above its I_c, the gate line has the same power-law effect on V_S whether I_G is above or below its I_c (estimated from relative line widths and the sensor line I_c). Hence, flux flow in the gate line does not seem to be a threshold for inducing the observed increments in the sensor flux-flow resistance. It is not clear whether superconductivity is required for the material of the gate line, and this too will be explored in future work.

Various numerical values of characterization are drawn from the data on FFD # 6 and 8 are listed in Table III. For digital circuit (i.e., switch) applications of these FFD, the appropriate transfer characterization parameter is ΔV, or $\Delta V/V_{SO}$, the fractional change in output voltage when I_G is incremented from 0 to I_G. For this switching action we have found that the best results occur when the FFD is close to but just below T_{co} and the sensor is biased just above its I_c. Under these conditions the power dissipated by the sensor will be relatively small, also. As listed in the Table the maximum observed was a tenfold change in the output voltage V_S, with an OFF-state heat dissipation of ~ 0.3 μW.

The small-signal transfer characteristics, appropriate to analog circuit applications such as amplification, is the transresistance $R_T = \delta V_S/\delta I_G$. The FFD is somewhat analogous to a semiconductor-based field effect transistor (FET) but with the roles of current and voltage reversed, i.e., in the FFD a current in the gate controls a voltage in the sensor (channel). Our FFD reached values of R_T ~ 0.3 Ω, and, as with the large-signal characteristics, this occurred when the FFD was just below T_{co} and just above I_c.

TABLE III. Three-terminal characteristics of the flux-flow devices (FFD). The *sensor* line (or source-drain) has a 4-point probe contact, while the *gate* line (or control line) has a 2-point probe contact. No intentional external magnetic fields are present. $\Delta T = T_{co} - T$. I_c is the critical current (1 μV criterion) and I_S is the constant bias current in the sensor line. I_G is the current in the gate line. V_S is the sensor-line voltage (i.e., the output) at I_S and I_G, and V_{So} the value at I_G=0. The large-signal characteristic for these devices is $\Delta V/V_{So}$, the fractional change in output voltage when I_G is incremented from 0 to I_G. The small-signal transfer characteristic for these devices is the transresistance $R_T = \delta V_S/\delta I_G$.

FFD #	T (K)	ΔT (K)	I_c (mA)	I_S (mA)	I_G (mA)	V_S (mV)	$\Delta V/V_{So}$	R_T (mΩ)
6	80	7.5	1.8	2.0	0	0.15	--	--
					20.8	0.35	1.3	--
				2.3	0	0.20	--	--
					20.8	0.60	2.0	--
				3.6	0	1.10	--	--
					20.8	1.7	0.55	--
				4.15	0	2.25	--	--
					2.3	2.27	0.007	14
					7.2	2.4	0.067	44
					15.0	2.8	0.24	93
					20.8	3.2	0.44	128
8	79.0	4.6	7.1	8.53	0	0.060	--	--
					10	0.21	2.5	20
				9.94	0	0.35	--	--
					10	0.87	1.5	88
	81.0	2.6	2.5	3.5	0	0.047	--	--
					10	0.15	2.1	30
				5.0	0	0.45	--	--
					10	1.15	1.6	110
	82.1	1.5	1.1	1.37	0	0.020	--	--
					5.0	0.031	0.55	7
					7.0	0.051	1.55	18
					10	0.22	10	287
				1.60	0	0.091	--	--
					1.9	0.104	0.14	13
					6.6	0.181	0.99	44
					10	0.451	4.0	205
				2.28	0	0.42	--	--
					1.3	0.44	0.05	21
					3.0	0.50	0.18	48
					6.5	0.75	0.79	104

PUBLICATIONS PLANNED

The results described under Task VI, above, are in our estimation clearly of sufficient scientific quality and interest to the research community to warrant publication. As is customary, we will first polish the details somewhat, but then prepare a manuscript, in the near future.

PROFESSIONAL PERSONNEL

Superconductivity Group At AFR

The Superconductivity Group at AFR, which is managed by the P.I. on this contract (Fenner), presently has in progress two SBIR Phase II contracts (including [1]) and two Phase I contracts. All of these deal with HTSC superconductor devices, especially IR detectors and flux-flow devices. Thus many of the specific project results are useful for the general goals of the other programs, including the present one.

In April of 1992, Dr. Lahmer Lynds, who recently retired from *United Technologies Research Center* (UTRC) after 20 years with them, will begin part-time work with the *Superconductivity Group at AFR, Inc.* Dr. Lynds has made many important contributions to HTSC research and has been a central figure in the laser ablation and film deposition technique, since its beginning. He is the author of many articles on these subjects.

A one-page summary of the staff, facilities and contracts for the Superconductivity Group is attached as APPENDIX A, to the Phase II proposal.

Consultant: Prof. J.I. Budnick

In the past year, we have developed a close and active collaboration with Prof. J.I. Budnick and his research group at The University of Connecticut. This collaboration is now giving us access to considerable expertise and facilities for superconductor magnetic-property evaluation. He is one of the leading experts in superconductor flux-flow dynamics and has contributed valuable observations to the efforts of the present contract.

Vitae of Senior Personnel

Principal Investigator

Dr. David B. Fenner, Senior Physicist and Manager of the Superconductivity Group at Advanced Fuel Research, Inc. has been the **Principal Investigator** on this program. Dr. Fenner received his Ph. D. in physics from Washington University in 1976. As Manager of the Superconductivity Group at AFR, he is responsible for R&D on electronic materials and devices. He has a broad background in applied physics including low-temperature physics, ultrasonics, phase transitions and critical phenomena, and polymer physics. Most recently, he has worked in silicon surface and interface physics and chemistry, including the use of x-ray photoemission and Auger spectroscopy (XPS and AES) and other ultrahigh vacuum techniques, molecular beam epitaxy (MBE) of gallium arsenide films on silicon, and pulsed laser deposition (PLD) of ceramic oxide films (e.g., high-temperature superconductors) on silicon. He was a consultant for the Xerox Palo Alto Research Center (PARC) over three years (1988 to 1990) working in the Electronic Materials Laboratory and funded by an NSF grant via Santa Clara University (nearby to PARC), where he was a tenured Associate Professor since 1986. He taught at Santa Clara for nine years until joining AFR in June of 1990. At AFR, he has been awarded (P.I.) on seven SBIR projects, and served as Technical Supervisor on two others. He has about 50 publications, including 16 in high temperature superconductor films, 5 in thin-films growth on Si by pulsed laser deposition, 4 in GaAs heteroepitaxial films on Si, 2 in Si surface analysis, 12 in polymer thermal physics, 13 in liquid mixture critical phenomena, and 4 in low temperature physics and liquid helium. He is a co-inventor with the Xerox group of a pending patent for epitaxial high-temperature superconductor films on silicon, and is currently filing for a patent on an architecture for superconducting interconnects and another for on-chip spectroscopy with superconducting bolometers. He is a member of the American Physical Society, Materials Research Society, IEEE Electron Devices Society, and American Association For Advancement of Science.

Other Key Personnel At AFR

Dr. Peter R. Solomon President of Advanced Fuel Research, Inc., has been **Program Manager** on this project. Dr. Solomon is a physicist with extensive experience in performing and managing interdisciplinary experimental and theoretical research in several fields including superconductivity, electron spin resonance, solid state physics, and work during the last ten years in energy and hydrocarbon research. He is the inventor of the superconducting DC transformer and has contributed to the understanding of flux flow in superconductors. He has guided the development of FT-IR as an on-line in-situ monitor in high temperature reacting systems. He also developed the use of FT-IR as a tool for quantitative functional group determination in coals and other hydrocarbons. Dr. Solomon is the author of over 14 publications and 3 patents on superconductivity. He has more than 80 publications and 4 patents on hydrocarbon energy research, 3 on electron spin resonance, and 10 on solid-state devices, including a book, The Gunn-Hilsum Effect. Dr. Solomon received his Ph. D. in physics in 1965 from Columbia University. Honors include his B.S., Magna cum Laude, the United Technologies Award for Research, and the ACS Fuel Division 'Richard A. Glenn Award'. He is a member of Phi Beta Kappa, Sigma Xi; the American Physical Society, Secretary-Treasurer, Vice-Chairman and Chairman of the New England Section; the American Chemical Society, Chairman of the Fuel Chemistry Division; the National Academy of Sciences, Committeeman; and the Combustion Institute. Dr. Solomon has managed research contracts for the Department of Defense, the Department of Energy, the National Science Foundation, the Environment Protection Agency, the Gas Research Institute, and the Electric Power Research Institute, totaling over $11,000,000 since 1976. He is the Past Chairman of the Fuel Chemistry Division of the American Chemical Society.

Dr. David G. Hamblen is the Vice-President of Advanced Fuel Research, Inc. Dr. Hamblen is responsible for directing and performing research in various new technology areas, including HTSC. He is also responsible for both theoretical and experimental studies of hydrocarbon fuels using FT-IR and x-ray microanalysis for diagnostics, and computer models for the pyrolysis and combustion simulations. Dr. Hamblen has had extensive experience in the field of low temperature physics and superconductivity. He participated in the design and construction of the first dilution refrigerator in this country, and has performed specific heat and magnetic susceptibility measurements on superconductors in the millikelvin range. He was involved in a program at MIT to construct and test a 2MVA alternator using superconducting field windings. Dr. Hamblen received his Ph. D. in physics from the University of Illinois in 1969. His thesis research involved the measurements of the critical magnetic field of superconducting molybdenum and cadmium. He has been Principal or Co-principal investigator on contracts and grants for the Department of Defense, the Environmental Protection Agency, the National Science Foundation, and the Department of Energy, totaling over $5 million since 1979. He has 28 research publications, 26 in fuel science, and two in solid-state physics. He is a member of the American Physical Society, the IEEE, and Sigma Xi.

Qi Li is a Staff Physicist in the Superconductivity Group at Advanced Fuel Research, Inc. He recently defended his PhD. dissertation work at the University of Maryland, and it is expected to be awarded in 1992. Before joining AFR in November of 1990, he spent five years as a guest scientist at the National Institute of Standards and Technology in Maryland working with both the neutron radiation group and the photon physics group. During this period of time Mr. Li gained extensive experience on condensed matter physics and applied laser science. His areas of expertise include non-linear optics, resonance enhanced multiphoton ionization spectroscopy, interaction of intense laser beams with solids, neutron diffraction and low temperature properties of superconducting and magnetic superconducting materials. At AFR his responsibilities have been directed toward thin-film deposition of metal oxides and II-VI compound semiconductors using the method of pulsed laser deposition (or ablation). He has successfully grown YSZ films on silicon wafers with epitaxial quality comparable to the current world's record for that system. Most recently, he has successfully grown YBCO films on ultrathin Si wafer membranes (only 3 μm thick). This technology holds promise for fabrication of high-performance transition-edge IR detectors (bolometers).

INTERACTIONS

Conference Activity

Since the most exciting results of this brief (six month) contract occurred only quite recently, we have not yet presented it specifically at conference. However, we have presented and are presenting soon results from other SBIR projects. See footnotes # 5 - 7 and 15 - 20, below.

Consulting Activity

None.

Collaboration Activity

As described in the text above, we have had a very fruitful collaborative relationship with three university research groups. First, we have collaborated with Prof. J.I. Budnick's superconductivity group in the Physics Department at the *University of Connecticut*. That work covered a variety of issues, especially those related to magnetic properties and flux-flow dynamics in HTSC materials. Second, we have very useful collaboration with Prof. H.D. Drew's group in the Physics Department and the Center for Superconductivity Research at the *University of Maryland*. That work centered on IR analysis at low temperatures and high magnetic fields. Thirdly, we have most recently collaborated with Prof. H. Zhang's group in the Department of Materials Science at *Northwestern University*. Their considerable skills and experience were very helpful in transmission electron microscopy of some of our thin-film samples using their new state-of-the-art microscope.

DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

None filed at the time of this *Report* for any work based on this particular Phase I activity. The new FFD designs that were described under Task V, above, are on the verge of having a sufficient demonstration of new aspects of the FFD and particular implementations such that a patent disclosure will be clearly warranted. AFR and Fenner have recently filed a patent application based on the work of previous SBIR Phase I program for DARPA [2], in the area of thin-film microelectronic interconnect devices.

CONCLUSIONS

This Phase I project has *successfully* demonstrated a coherent, promising and feasible plan for the R&D of a superconducting microelectronic device. While there has been a small shift in the emphasis on certain technical details away from those originally envisioned in the Phase I proposal, the technical strength of the program is now ensured by this focusing process, which has come about through a process of actual fabrication and successful testing of these devices. We show in this *Final Report* that at AFR we have the skills and facilities to make excellent quality high-temperature superconductor films on silicon wafers, pattern them into various shapes (e.g., narrow lines) for device design testing, protect the superconductor surface, make electrical and optical connections, and fabricate larger assembled structures, as needed (e.g., bond together multiple layers of these superconductors on silicon). We have demonstrated that good quality superconducting films can be fabricated on very thin Si wafers, which also open up many applications-technology possibilities.

In this Phase I program we have fabricated the first known HTSC flux-flow device (FFD) structures on silicon wafers, and we are among a very small number of groups known to have explored HTSC three-terminal FFD. Our devices and the characterizations we have done, have added important new evidence as to the details of the basic device physics. In particular, we have demonstrated that: 1) Thin-film FFD do *not* need to rely on more difficult to fabricate, multi-HTSC-layer structures, or thinned microbridge or weak-linked regions, although the latter may eventually prove to be useful. 2) Such FFD in three-terminal configurations show *considerably enhanced device transfer functions* (large-signal output voltage swing, or small-signal transresistance), well above that measured for uniform external magnetic field control. This advantage seems especially ripe for further development. 3) The transfer functions are strengthened also by operation of the FFD near, but just below, the zero-resistance point in the superconducting transition, and near, but just above, the critical bias current for the onset of flux-flow resistance. 4) The potential applications to digital and/or switch circuits seem to be much more promising for our FFD, relative to those few reported by others, as a direct consequence of the distinctly nonlinear characteristics we have observed. 5) As a *switch*, the fabricated FFD were able to drive output swings of millivolts from milliamps input with *less than microwatts* heat dissipation in the OFF state.

Reports of others show in detail that FFD analog operation with power gain is possible up to at least 10 GHz. Taken in conjunction with this, our results demonstrate FFD performance characteristics which compare quite favorably with competing technologies of semiconductor and low-temperature superconductor devices.

FOOTNOTES TO THE TEXT

1. Dept. of Energy, SBIR Phase II, # DE-FG01-90ER81084, Sep 90 to Sep 92, D.B. Fenner P.I.
2. DARPA, SBIR Phase I, # DAAH01-91-C-R026, 24 Apr 91 to 31 Oct 91, D.B. Fenner P.I.
3. D.K. Fork, D.B. Fenner, G.A.N. Connell, J.M. Philips, and T.H. Geballe, Appl. Phys. Lett., **57**, 1137 (Sep 1990).
4. D.K. Fork, D.B. Fenner, R. Barton, J.M. Philips, G.A.N. Connell, J.B. Boyce, and T.H. Geballe, Appl. Phys. Lett., **57**, 1161 (Sep 1990).
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